Evaluation of mensuration equipment for upper-stem height and diameter measurements

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Abstract
To assess standing timber volume and value, inventory and analysis methods are needed that can capture the precise stem form of individual trees. Most taper or tree form models perform much better if upper-stem diameter measurements are available, in addition to DBH and height values. This paper reports on the testing of hand-held tools for upper stem diameter and height measurements. The evaluation of the equipment was based on the accuracy of diameter and height measurements, the time required to carry out these measurements and the cost of the equipment. The test involved familiarisation with the equipment, followed by diameter and height measurements on four Norway spruce trees at ⅓ and ⅗ of total tree height. Both experienced and inexperienced professional foresters were included in the study.

Keywords: *Impulse Laser, TruPulse, LaserAce, Masser, Haglöf.*

Introduction

Standing volume is the most important statistic describing the economic value of forest resources. There is an increasing demand for single tree volume and taper models in Ireland due to a transition towards mixed-species stands in recent years (Forest Service 2007). Stratified sampling with permanent sample plots in the current Irish National Forest Inventory (NFI) also necessitates the use of single tree models for forest resource assessments. Pre-harvest evaluation studies conducted in Ireland highlight the requirement for an alternative to the currently used British Forestry Commission Tariff Chart system (Matthews and Mackie 2006) to better reflect regional and site specific variations in stem taper (Nieuwenhuis et al. 1999).

Therefore, volume calculation tools are required that are based on easily measurable parameters of individual standing trees, such as stem diameter and tree height. Apart from total tree volume, estimates are also required for assortments based on dimensional thresholds, e.g. the volume in the stem section between a small end diameter 7 cm and a large end diameter 14 cm. This requires the application of suitable taper models. Such models may either be segmented (e.g. Max and Burkhart 1976, Petersson 1999) or continuous (e.g. Kozak 1988, Riemer

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et al. 1995). The continuous or variable-form taper models are able to represent diameter continuously along the stem from ground to tip (Lee et al. 2003). For these volume and taper modeling approaches to produce good results, upper-stem diameter(s) should be included in the data, in addition to the diameter at breast height and tree height.

During the last 50 years, a considerable amount of data has been collected on tree stems for the main coniferous tree species in Ireland. These data have been used for the derivation of Irish stem volume models that can replace or complement British Forestry Commission tariff charts and associated functions (Matthews and Mackie 2006). Generalized stem profile models have been developed that can be used for both the calculation of stem volume and for the calculation of the volume of any part of the stem. This allows for the estimation of the potential output of assortments defined by length, and small- and large-end diameter specifications.

The objective of this study was to describe and evaluate the different inventory tools available for collecting the necessary data for use in the developed stem profile models. All relevant equipment and tools that can be used for upper stem diameter and height measurements were obtained and included in a field-testing project to determine their suitability for everyday use in inventory and management practices. This determination took into account the accuracy of the measurements, the time required to take the measurements and the price of the equipment. All these factors were then included in an overall ranking exercise. Professional foresters experienced and inexperienced in inventory work were included in the field-testing; this paper reports on the results of the project.

Material and methods

Equipment

Six pieces of equipment were tested, most of which can measure both diameters and height (Table 1). However, the Masser tool cannot be used for upper-stem height measurements and the Haglöf calipers can only be used for diameter measurements.

Test site

The equipment was tested at a site in Co. Wicklow with the following characteristics:

Name:	Knockrath Forest;
Townland:	Ballyhad Lower;
Age:	47 years (planted in 1964);
Species:	Norway spruce (*Picea abies* (L.) H.Karst.) with some Sitka spruce (*Picea sitchensis* (Bong.) Carr.);
Stocking:	526 stems ha^{-1}.

Table 1: *Key for the measurement tool codes used in the graphs and tables, listing the range of inventory tools assessed in the study. Each test involved a separate tool.*

Test number	Tool	Product information
1	Impulse Laser Rangefinder with fixed scope	http://www.forestry-suppliers.com/product_pages/View_Catalog_Page.asp?mi=1376
2	Impulse Laser Rangefinder and Criterion RD1000 Dendrometer with adjustable scope	http://www.forestry-suppliers.com/product_pages/View_Catalog_Page.asp?mi=3873
3	TruPulse 360 R Laser Rangefinder with adapted graduated scope	http://www.lasertech.com/TruPulse-Laser-Rangefinder.aspx
4	LaserAce 1000 Laser Rangefinder	http://www.forestry-suppliers.com/product_pages/View_Catalog_Page.asp?mi=384
5	Masser RC3h	http://www.masser.fi/product-category/rc3h-bt/ Cannot measure height of upper measurement point
6	Haglöf Gator Eyes	http://www.forestry-suppliers.com/product_pages/View_Catalog_Page.asp?mi=8761 Cannot measure heights

Field test layout

The test consisted of carrying out measurements on five Norway spruce trees, one of which was the control tree and the other four were test trees. The control tree was used to give the tester a chance to get familiar with the equipment. The testers were given the correct values of each measurement after completing it, and they could repeat the measurements if they felt this would be beneficial. The control tree characteristics were:

- all branches removed within the measurement area;
- clear view of the stem at the points of measurement.

After familiarizing themselves with the equipment using the control tree, the testers carried out measurements on each of the four test trees with each piece of equipment. With the Masser (test 5) and Haglöf (test 6) only two measurements could be made. The test trees' characteristics were:

- natural state;
- not brashed;
- measurement points possibly obscured;
- testing of equipment under normal conditions;
- two points marked for test at ⅓ and ⅗ of total tree height.

Data overview

Six people took part in the testing of the equipment, three of them experienced forest inventory staff and three inexperienced colleagues. Each tester made four measurements with a piece of equipment, where possible: two height measurements and two diameter measurements. Due to time constraints, not all testers completed measurements with all pieces of equipment. The measurements by all testers were made from the same direction to the trees and the testers could select the distance to the trees from which the measurements were taken freely. The true values were obtained by climbing the trees and measuring the heights of the measuring points with a tape and the diameters with a callipers perpendicular to the direction from which the testers took their measurements.

The results of the evaluation process presented in this paper are based on the data for these six testers. In the first section, we deal with diameter, and in the second section, we focus on height. In the third section, diameter and height were analysed together, while in section 4 volume was examined. Following these sections, dealing with measurement accuracy, the time required to carry out the measurements and the cost of the equipment were analysed to arrive at a cost per measurement value. Finally, in the Discussion and Conclusion section, the accuracy results are combined with the cost findings to produce a ranking of the equipment, for both experienced users and for the inexperienced users.

Results

Diameter

Relative errors for the lower and upper diameter points are presented in Figure 1, for experienced and inexperienced testers separately. The same trends towards higher accuracies for the lower measurements are revealed, and the accuracies for the experienced testers seem lower than those for the inexperienced ones. When lower and upper errors are analysed together for each tree and each test (only tests 1 to 4 are included as these pieces

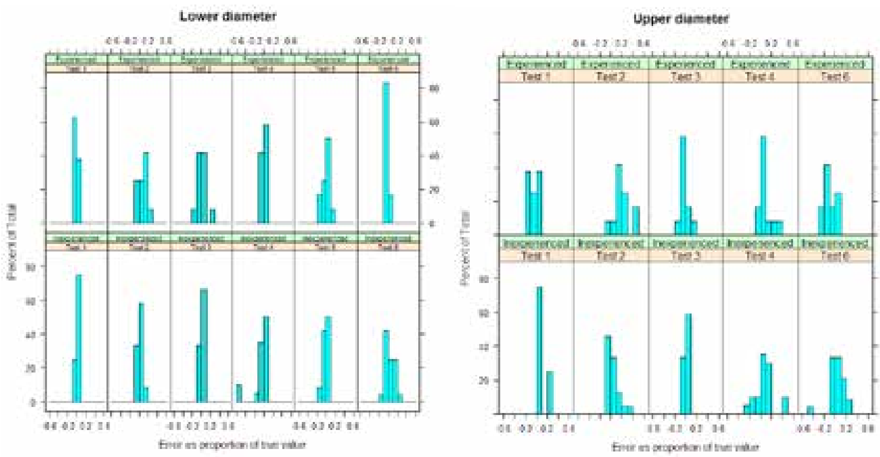

Figure 1: *Tests 1 to 6 (see Table 1 for list of equipment used in each test) compared diameter estimates made by experienced and inexperienced operators with true measurements. Relative lower (left) and upper (right) diameter errors classified by experience level and test method. (Test 5 did not include upper diameter measurements.)*

of equipment can measure both diameters) clear differences start to appear, with tests 1 and 3 producing much better results than test 2 and, especially, test 4 (Figure 2).*Height*

The results for the height measurements are in general, very good, both for the lower and upper points, but when the accuracies for the individual pieces of equipment are analysed for both the lower and upper points, a clear trend appears where for all tests the accuracies are reduced at the upper point, especially for tests 2 and 4. Analysis by test and experience level indicated difficulties with test 4 for both experienced (at the upper point) and inexperienced (at upper and lower points) testers (Figure 3).

An analysis of the relative errors by tester, test and tree, for the lower and upper measurements combined, clearly indicated that test 4 had the largest errors for a number of testers (Figure 4) and errors occurred both at the lower and upper points. A detailed analysis of test 4 revealed that especially some of the inexperience testers had problems with this piece of equipment. test 2, which appears to produce good results, when analysed separately, produced very small errors except for one observation by an experienced tester.

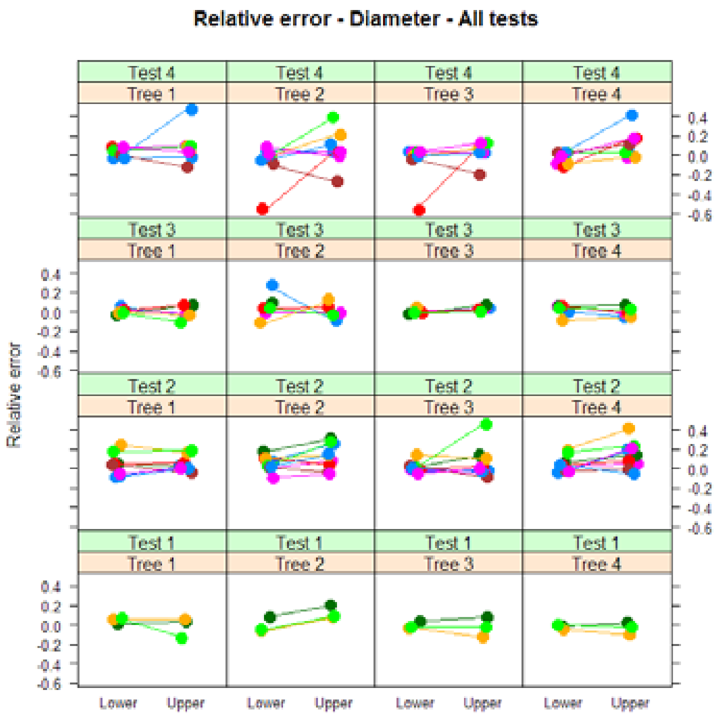

Figure 2: *Relative diameter error ((true – test) / true) classified by tester (colours), test, tree and measurement point (lower and upper). (Test 5 did not perform upper stem measurements; test 6 did not perform height measurements.)*

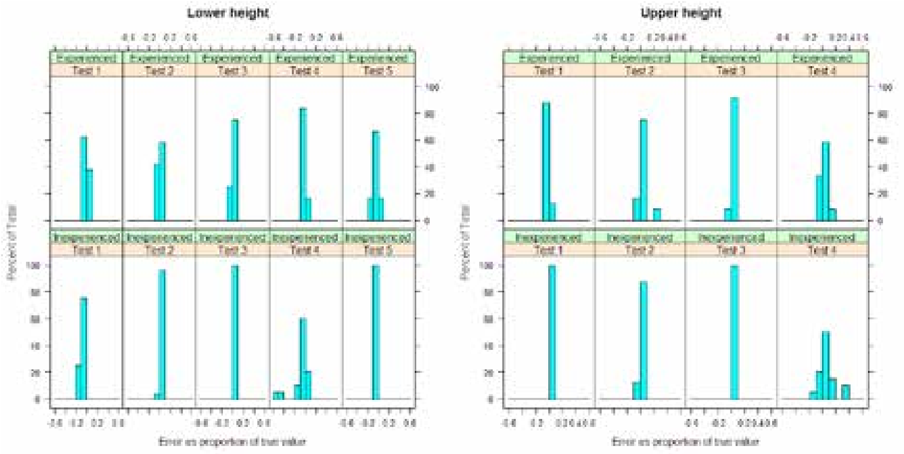

Figure 3: *Relative lower (left) and upper (right) height errors classified by level of experience and test method. (Note: test 5 did not perform upper stem measurements; test 6 does not perform height measurements.)*

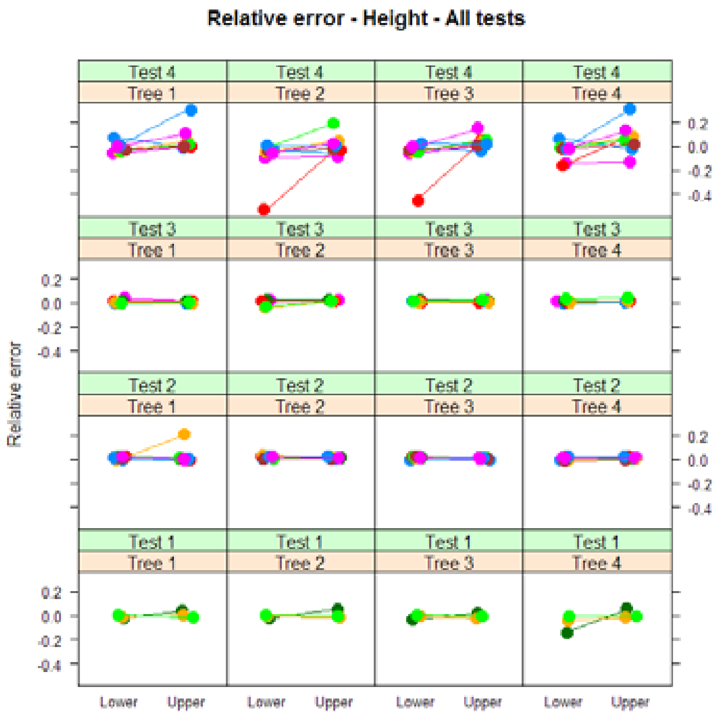

Figure 4: *Relative height errors grouped by testers (colours), tests, trees and measurement point (lower and upper).*

Diameter and height combined

To investigate how the pieces of equipment performed at both height and diameter measurements, combined graphs of relative errors have been produced. When experienced and inexperienced testers are analysed separately, tests 3 and 1 produced the best results (it should be noted that the results for test 5 only relate to the lower stem measurements) (Figure 5).

When analysing the relative errors separately for each test, for each tree for each tester, and looking at the combination of diameter and height, it is obvious that some pieces of equipment performed much better than others (Figure 6). Tests 1 and 3 show much better results than tests 2 and 4, with test 4 producing the worst results. In the test 3 data, it is interesting that the tree 2 measurements, both at the lower and upper points, produced larger errors than those for the other trees.

Volume

To get an indication of how the measurements of diameter and height combine into volume estimation, the volume of the frustum defined by upper and lower diameter and the height difference between them was calculated. The frustum volume formula is:

$$\text{Frustum volume } (m^3) = \pi\, h\, (D^2 + d^2 + D\, d)/12 \qquad (1)$$

where *D* is the lower diameter (m), *d* the upper diameter (m) and *h* is the difference (m) between the upper and lower heights.

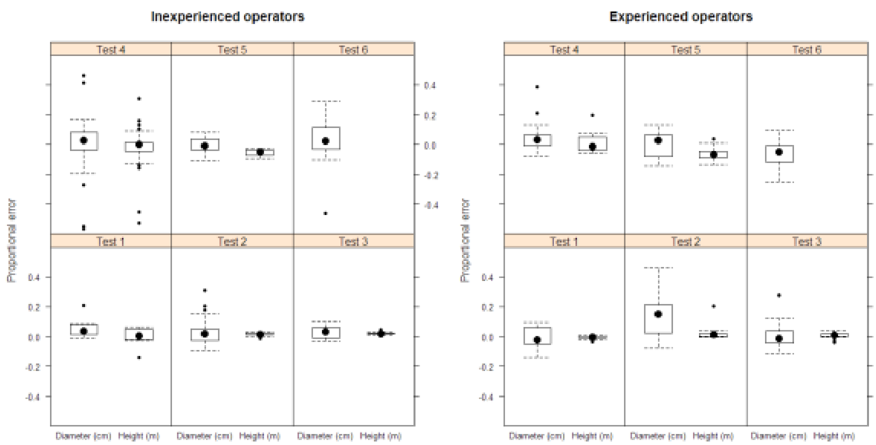

Figure 5: *Relative error classified by measurement type and test method for* inexperienced *(left) and* experienced *(right) operators. (Note: test 5 did not perform upper stem measurements; test 6 did not perform height measurements.)*

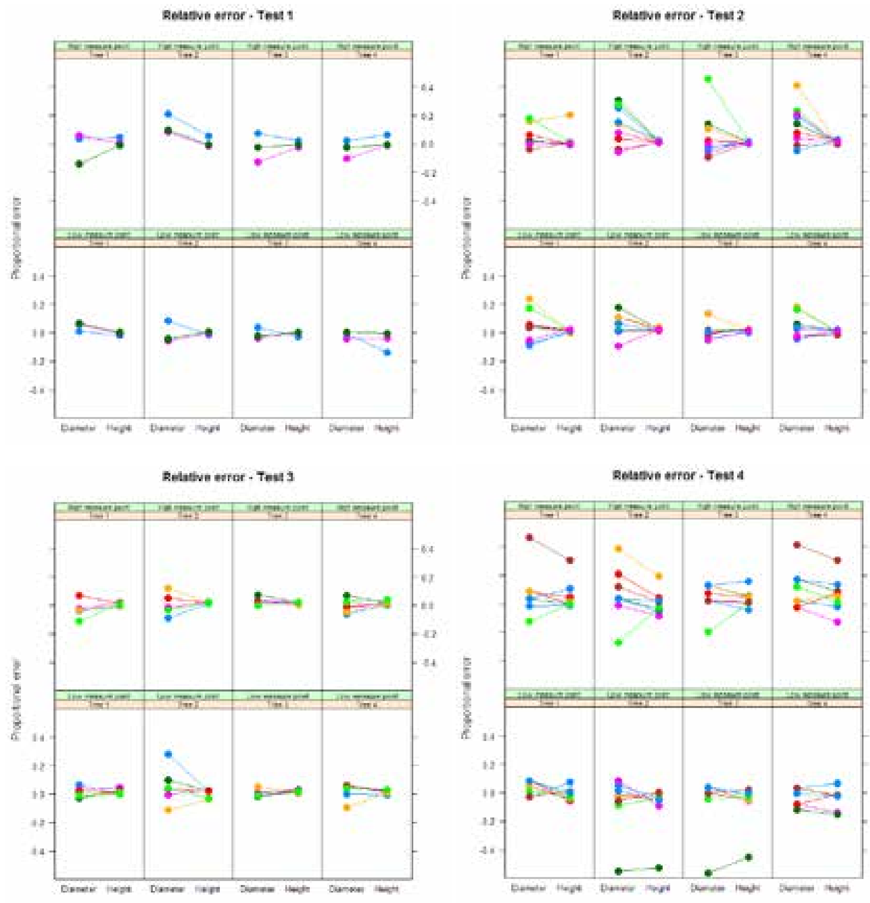

Figure 6: *The relationship between height and diameter errors classified by tree, tester (colour) and measurement point (low and high), for Test 1 (top left), Test 2 (top right), Test 3 (bottom left) and Test 4 (bottom right). Lines join height-diameter pairs of measurements i.e. measurements at the same point on the same tree by the same tester.*

Comparions were made using combinations of the actual and estimated values (Figure 7). A general skewness is identified (the vast majority of ratio values > 1.0), indicating that the true volumes were on average larger than those estimated using one or both estimated components. The results demonstrated the overall better result using test 3. Test 2 performed very well for the true diameter – estimated height combination, apart from one outlier (Figure 7b), but very badly for the test diameter – true height combination (Figure 7a). In Figure 8, the same analysis is shown separately for inexperienced and experienced testers. The strong performance of test 3 for both sets of testers for the test diameter – test height combination is very apparent.

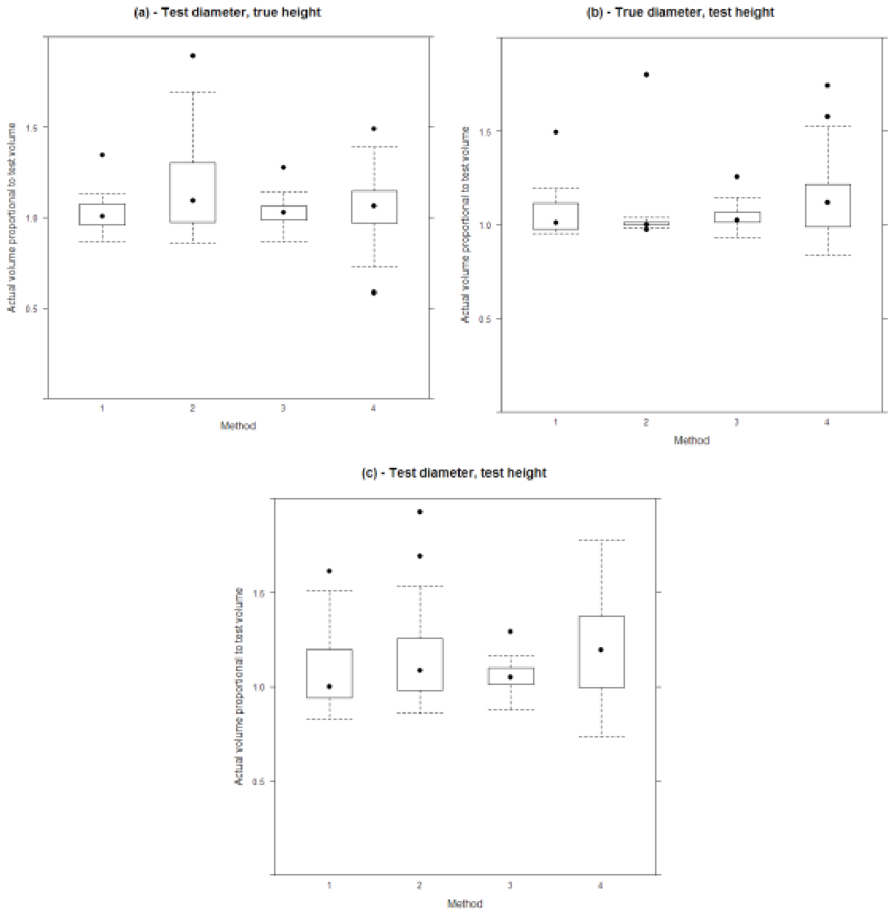

Figure 7: *Box-whisker plots of relative frustum volumes classified by method (test 1 – 4). The variable presented is the ratio of the frustum volume calculated using the* true height *and* diameter *measurements and the frustum volume calculated using either* estimated diameter *and* true height *(panel a), estimated height and true diameter (panel b) or both* estimated height *and* estimated diameter *(panel c).*

Time consumption

Apart from the accuracy of the measurements, another criterion that should be used to evaluate the suitability of the test equipment for operational use is the time consumed in carrying out the measurements. Figure 9 illustrates that test 3 resulted in the best outcome for both inexperienced and experienced testers, while tests 1 and 2 worked well for experienced testers but not for inexperienced ones.

Cost effectiveness

Factors involved in cost effectiveness are the hourly cost of the equipment over the

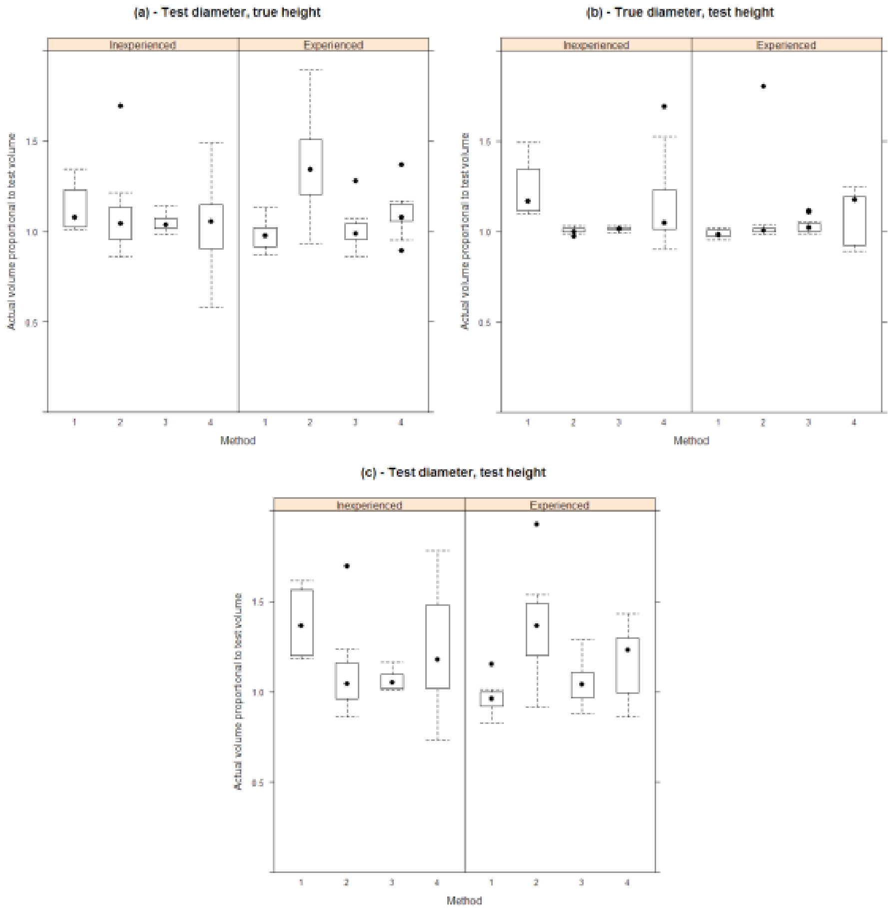

Figure 8: *Box-whisker plots of relative frustum volumes classified by method (tests 1 – 4) and experience level of operator (experienced, inexperienced). The variable presented is the ratio of the frustum volume calculated using the* true height *and* diameter *and the frustum volume calculated using either* estimated diameter *and* true height *(panel a),* estimated height *and* true diameter *(panel b), or both* estimated height *and* estimated diameter *(panel c).*

standard depreciation schedule, and the time required to carry out the measurements with the different pieces of equipment. These factors are summarised in Table 2. The final column combines the cost of the equipment with the mean measurement time observed per set of measurements, equipment type, and experience level. Test 3 resulted in the best outcome for both experienced and inexperienced users.

Discussion and Conclusions

The setup of the test introduced some artificial constraints that could have influenced the results. All measurements had to be taken from the same direction to ensure that

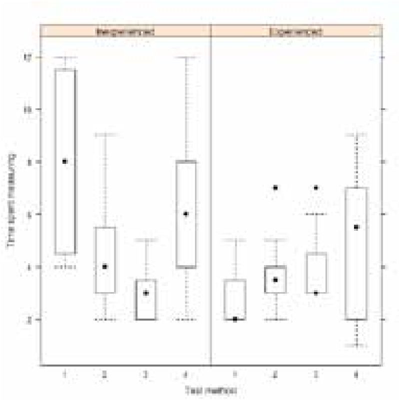

Figure 9: *Measurement time for each method (tests 1 – 4) classed by operator's level of experience.*

the same true diameters were assessed, and testers were forced to take the diameter measurements at the heights indicated on the stems. For the four pieces of equipment that were capable of measuring heights and diameters, these test requirements did not affect the outcome, except maybe in the case where the view of the stem at the measuring point was (partly) obscured from the direction of measurement and the tester, in practice, could have selected another measuring direction or a different measuring height to get a better view. However, the testers were free to change the distance from the trees from which the measurements were taken, so occlusion of the stems was not a real problem.

In general, the pieces of equipment performed either well overall or not at all. Equally, most of the pieces of equipment performed similarly for experienced and inexperienced users, with the exception of test 1, which came first for experienced

Table 2: *Costs (equipment purchase, correct for 2008) and costs per hour (assuming depreciation period of three years and a schedule of fifty, five-day weeks and eight-hour days (~ 6,000 hours), time taken per set of measurements (i.e. two heights and two diameters) and cost per set of measurements, for experienced and inexperienced users.*

Test	Cost (2008) (€)	Cost per hour (€ hr^{-1})	Time per set (experienced / inexperienced) (hr set^{-1})	Cost per set (experienced / inexperienced) (€ set^{-1})
1	3,817	0.63	0.048 / 0.127	0.03 / 0.08
2	4,170	0.69	0.058 / 0.072	0.04 / 0.05
3	1,500	0.25	0.080 / 0.040	0.02 / 0.01
4	1,620	0.27	0.074 / 0.011	0.02 / 0.03
5	945	0.16	NA	NA
6	595	0.10	NA	NA

Table 3: *Overall assessment rankings, for both experienced and inexperienced users, based on the cost of the equipment, the time taken to carry out the measurements, and the accuracies obtained for height and diameter measurements and volume estimation.*

	Experienced users						
Equipment	**Test**	**height**	**diameter**	**volume**	**cost**	**time**	**Sum of rankings**
Impulse	1	2	1	1	3	1	8
Criterion	2	3	4	4	4	2	17
TruPulse	3	1	2	2	1	3	9
LaserAce	4	4	3	3	2	4	16

	Inexperienced users						
Equipment	**Test**	**height**	**diameter**	**volume**	**cost**	**time**	**Sum of rankings**
Impulse	1	2	2	3	3	4	14
Criterion	2	3	3	2	4	2	14
TruPulse	3	1	1	1	1	1	5
LaserAce	4	4	4	4	2	3	17

users but a distant shared second for inexperienced users.

Based on the accuracy levels obtained for height, diameter measurements and volume estimation, combined with the cost of the equipment and the time required to do the measurements, a ranking of the equipment has been drawn up for each factor and for all factors combined (assuming equal weights) (Table 3). Test 1 comes out on top for experienced users, very closely flowed by test 3. Test 3 performed best with inexperienced users, while test 1 provided low quality results for inexperienced ones. Test 3 would be the recommended equipment if it was to be used by both experienced and inexperienced users. Of course, the weightings that different users might put on accuracy, efficiency and price could influence the outcome of the overall evaluation.

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